

SPECIMEN CURRENT MAPPER

CROSS-REFERENCE TO RELATED APPLICATIONS

5 [0001] This application is a continuation in part of U.S. Patent Application 10/434,977, filed 9 May 2003, which is a continuation in part of U.S. Patent Application 10/209,087, filed 30 July 2002. The disclosures of these related applications are incorporated herein by reference.

FIELD OF THE INVENTION

10 [0002] The present invention relates generally to semiconductor device manufacturing and process control, and specifically to monitoring of process quality and uniformity.

BACKGROUND OF THE INVENTION

15 [0003] Contact hole production is a common step in semiconductor device manufacturing. The contact holes are typically used to make electrical connections to a semiconductor or metal layer through an overlying non-conducting (dielectric) layer, such as an oxide layer.
20 In order to produce contact holes, a layer of photoresist is first deposited on the wafer surface. The photoresist is exposed to patterned visible or ultraviolet radiation, hardened, and developed in order to form a "mask" over the wafer, with mask patterns corresponding to contact
25 hole locations. Then the wafer is transferred to an etch station where contact holes are formed through the dielectric layer, down to the underlying semiconductor or metallic layer. The photoresist mask is then removed, and the contact holes are filled with metal. A similar
30 masking and etching process is used in producing trenches or vias in the wafer surface.

[0004] In order to ensure consistent device performance, the depth, width, and bottom surface of contact openings must be carefully controlled at various locations across the wafer surface. (In the context of 5 the present patent application and in the claims, the term "contact openings" refers to all structures of the type described above, including contact holes, vias, and trenches.) Deviations in the dimensions of contact openings at a location on the wafer or across the wafer 10 surface can lead to variations in the contact resistance. If these variations are too large, they impact on device performance and can lead to loss of process yield. The manufacturing process must therefore be carefully monitored and controlled, not only in order to detect 15 deviations in formation of contact openings on individual devices, but also to monitor non-uniformities across the wafer surface. Early detection of process non-uniformity allows the device manufacturer to take corrective action, so as to ensure uniformly high yields and avoid the loss 20 of costly wafers in process.

[0005] Various methods for contact hole inspection are known in the art. One such method is described by Yamada et al., in "An In-Line Process Monitoring Method Using Electron Beam Induced Substrate 25 Current," in *Microelectronics-Reliability* 41:3 (March 2001), pages 455-459, which is incorporated herein by reference. The compensation current in an electron beam system, also known as the specimen current, is defined as the absorbed current that flows from the primary electron 30 beam to earth via the specimen (i.e., via the wafer). In other words, the specimen current is equal to the difference between the primary beam current and the total electron yield of the specimen due to secondary and backscattered electrons. The specimen current can be

either positive or negative, depending on whether the energy of the primary electron beam is in the positive- or negative-charging domain of the specimen. Yamada et al. directed an electron beam at single holes and groups 5 of holes in a silicon oxide surface layer overlying a silicon substrate, and measured the resultant compensation current. They found that the compensation current was a good indicator of hole-bottom oxide thickness, as well as of the hole diameter.

10 [0006] Yamada et al. describe further aspects of contact hole measurement in U.S. Patent Application Publication No. US 2002/0070738 A1, whose disclosure is incorporated herein by reference. Semiconductor devices are inspected by measuring the specimen current in an 15 area of a sample having no contact holes as a background value, and comparing this value to the current measured in the area of a hole. The current waveform is automatically evaluated in order to determine whether the measurement is indicative of a defect of the device or of 20 manufacturing equipment used in producing the device.

[0007] In U.S. Patent 6,559,662, whose disclosure is incorporated herein by reference, Yamada et al. describe a semiconductor device tester based on specimen current measurement. A plurality of measuring 25 positions on a sample are sequentially irradiated with electron beams having identical shapes. The currents produced in the sample due to irradiation at the individual measuring positions are measured, and the measurements are displayed on a two-dimensional plane as 30 a function of measuring position.

SUMMARY OF THE INVENTION

[0008] It is an object of some aspects of the present invention to provide improved methods and systems for monitoring production of contact openings.

5 **[0009]** In embodiments of the present invention, contact openings on a sample, typically a semiconductor wafer, are irradiated at multiple locations with a focused beam of charged particles, along a beam axis that deviates substantially in angle from a normal to the
10 surface of the sample. At each location, the specimen current is measured and recorded, along with coordinate information. The specimen current measurements over the entire sample, or a region of the sample, are mapped in graphical or in numerical form. The map facilitates
15 detection of deviations of the measured specimen current from benchmark values and of process non-uniformities over the sample that cause uneven etching of the contact openings.

[0010] The measured specimen current at each
20 location serves as a quantitative measure of the quality of contact openings at the location. Specimen current magnitude can serve as a measure of the thickness of the residue on the bottom of a contact opening. Typically, a high absolute value of the specimen current indicates
25 good contact to ground, while low absolute value indicates higher resistance to ground. The use of an angled beam of charged particles to irradiate the sample provides enhanced sensitivity to thin residue layers that may remain at the bottom of contact openings. The
30 combination of angling the beam and mapping the resultant specimen current thus provides a particularly sensitive, integrated picture of the accuracy and uniformity of the process that is used to create the contact openings.

[0011] The specimen current measurements described hereinabove may be made before a photoresist mask used in etching the contact openings is removed from the wafer. If the specimen current map indicates that 5 the contact openings have not been fully etched for all or a part of the wafer, the etching process can be adjusted and continued until the proper etch parameters are reached. Alternatively or additionally, the process variables may be adjusted to effect more precisely etched 10 holes and/or a more uniform distribution of these etched holes across the wafer surface. Such variables include, for example, lithographic alignment, photoresist application, stop layer thickness, and material deposition thickness.

15 [0012] There is therefore provided, in accordance with an embodiment of the present invention, a method for process monitoring, including:

20 [0013] receiving a sample having a first layer that is at least partly conductive and a second layer formed over the first layer, following production of contact openings in the second layer;

25 [0014] directing a beam of charged particles along a beam axis that deviates substantially in angle from a normal to a surface of the sample, so as to irradiate one or more of the contact openings in each of a plurality of locations distributed over at least a region of the sample;

30 [0015] measuring a specimen current flowing through the first layer in response to irradiation of the one or more of the contact openings at each of the plurality of locations; and

[0016] creating a map of at least the region of the sample indicating the specimen current measured in

response to the irradiation at the plurality of the locations.

[0017] The method may also include measuring a secondary electron current emitted from the sample 5 responsive to the beam of charged particles, and creating the map may include mapping the secondary electron current together with the specimen current.

[0018] In a disclosed embodiment, the method includes directing the beam of charged particles toward 10 one or more reference locations that are adjacent to at least one of the plurality of locations of the irradiated contact openings, and measuring the specimen current includes measuring reference values of the specimen current in response to the irradiation of the reference 15 locations, and creating the map includes subtracting the reference values from the specimen current measured in response to the irradiation of the contact openings to generate subtracted current values, and using the subtracted current values in creating the map.

[0019] Typically, creating the map includes 20 assessing, based on the map, at least one of a characteristic depth and a characteristic width of the contact openings at each of the plurality of locations. Additionally or alternatively, creating the map includes 25 assessing, based on the map, non-uniformities in a process used to create the contact openings. Assessing the non-uniformities may include assessing variations over the region of the sample, as well as assessing variations between different, first and second samples. 30 The method may further include applying corrective action to the process responsively to the map.

[0020] In a disclosed embodiment, the sample includes a semiconductor wafer, and at least some of the locations are located on different dies of the wafer.

Typically, directing the beam of charged particles includes selecting the locations to irradiate such that the one or more of the contact openings in each location among the plurality of locations are characteristic of 5 the contact openings in a respective area of the location. Further typically, at least one of the contact openings is a contact hole or a trench.

[0021] In one embodiment, the contact openings have side walls and a bottom, and directing the beam of 10 charged particles includes angling the beam so that more of the charged particles strike the side walls than strike the bottom.

[0022] Typically, creating the map includes assessing, based on the map, whether a contaminant 15 residue is present within the contact openings.

[0023] In another embodiment, the method includes negatively precharging the surface of the sample in proximity the contact openings, so as to facilitate measurement of the specimen current.

20 [0024] There is also provided, in accordance with an embodiment of the present invention, apparatus for testing a sample having a first layer that is at least partly conductive and a second layer formed over the first layer, following production of contact openings 25 in the second layer, the apparatus including:

[0025] a particle beam source adapted to direct a beam of charged particles along a beam axis that deviates substantially in angle from a normal to a 30 surface of the sample, so as to irradiate one or more of the contact openings in each of a plurality of locations distributed over at least a region of the sample;

[0026] a current measuring device adapted to measure a specimen current flowing through the first

layer in response to irradiation of the one or more of the contact openings at each of the plurality of locations; and

[0027] a controller adapted to create a map of 5 at least the region of the sample indicating the specimen current measured in response to the irradiation at the plurality of locations.

[0028] There is additionally provided, in accordance with an embodiment of the present invention, a 10 method for process monitoring, including:

[0029] receiving a sample having a first layer that is at least partly conductive and a second layer formed over the first layer, following production of a structure in the first layer and contact openings in the 15 second layer;

[0030] directing a beam of charged particles to irradiate one or more of the contact openings in each of a plurality of locations distributed over at least a region of the sample;

20 [0031] measuring a specimen current flowing through the first layer in response to irradiation of the one or more of the contact openings at each of the plurality of locations; and

25 [0032] assessing an alignment between the contact openings in the second layer and a structure in the first layer at each of the plurality of locations responsively to the measured specimen current.

30 [0033] Typically, assessing the alignment includes creating a map of at least the region of the sample indicative of the alignment.

[0034] There is further provided, in accordance with an embodiment of the present invention, apparatus for testing a sample having a first layer that is at

least partly conductive and a second layer formed over the first layer, following production of a structure in the first layer and contact openings in the second layer, the apparatus including:

5 [0035] a particle beam source adapted to direct a beam of charged particles so as to irradiate one or more of the contact openings in each of a plurality of locations distributed over at least a region of the sample;

10 [0036] a current measuring device adapted to measure a specimen current flowing through the first layer in response to irradiation of the one or more of the contact openings at each of the plurality of locations; and

15 [0037] a controller adapted to assess an alignment between the contact openings in the second layer and a structure in the first layer at each of the plurality of locations responsively to the measured specimen current.

20 [0038] The present invention will be more fully understood from the following detailed description of the preferred embodiments thereof, taken together with the drawings in which:

BRIEF DESCRIPTION OF THE DRAWINGS

25 [0039] Fig. 1A is a schematic top view of a semiconductor wafer with a pattern of contact holes formed thereon, in accordance with an embodiment of the present invention;

[0040] Fig. 1B is a schematic, sectional view of 30 the pattern of Fig. 1A, taken along a line 1B-1B;

[0041] Figs. 2A-2E are schematic, sectional illustrations of an area of a semiconductor wafer,

showing a contact hole etched into the wafer under different process conditions;

5 [0042] Fig. 3A is a schematic sectional illustration of an area of a semiconductor wafer, showing alignment between contact holes in different layers formed on the wafer;

[0043] Fig. 3B is a schematic top view of the area shown in Fig. 3A;

10 [0044] Fig. 3C is a schematic sectional illustration of an area of a semiconductor wafer, showing misalignment between contact holes in different layers formed on the wafer;

[0045] Fig. 3D is a schematic top view of the area shown in Fig. 3C;

15 [0046] Fig. 4A is a block diagram that schematically illustrates apparatus for contact hole inspection and specimen current mapping, in accordance with an embodiment of the present invention;

20 [0047] Fig. 4B is a schematic, sectional view of a contact hole on which an electron beam is incident at a non-normal angle, in accordance with an embodiment of the present invention;

25 [0048] Fig. 5 is a flow chart that schematically illustrates a method for specimen current mapping, in accordance with an embodiment of the present invention; and

30 [0049] Fig. 6 is a schematic representation of a specimen current map indicating specimen current measurements at locations across a wafer, in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION OF EMBODIMENTS

[0050] Reference is now made to Figs. 1A and 1B, which schematically illustrate a semiconductor wafer 20 and details of a pattern 22 of contact holes 26 formed thereon, in accordance with an embodiment of the present invention. Fig. 1A is a top view of the wafer, with the pattern shown enlarged in an inset. Fig. 1B is an enlarged, cross-sectional view of the pattern, taken along line 1B-1B in Fig. 1A. Pattern 22 may be a dedicated test pattern, for use in specimen current mapping, as described below, or it may comprise a group of production contact holes in a known location on wafer 20. (Exemplary test patterns are described in the above-mentioned U.S. Patent Application 10/209,087.) Although only the single pattern 22 is shown in Fig. 1A by way of example, multiple patterns of this sort, distributed over the surface of wafer 20, are used in specimen current mapping. The pattern may also include other types of contact openings (not shown), such as trenches or vias. Alternatively, specimen current measurements may be made and mapped on individual contact holes.

[0051] In a typical application, a dielectric oxide layer 30 is formed over a conductive or semiconductor underlying layer 28, and a layer of photoresist 32 is deposited on the dielectric layer. Layer 28 may comprise the silicon substrate of the wafer, or it may comprise an intermediate semiconductor or metal layer used as a part of devices fabricated on the substrate. Holes 26 are defined by photolithography, and are then etched through layer 30 down to underlying layer 28. A measurement of the specimen current generated when pattern 22 is irradiated by an electron beam is indicative of the extent to which layer 28 is exposed within the holes. To facilitate specimen current

measurement, a conductive contact pad 33 may be formed on the underside of wafer 20, below pattern 22.

[0052] Figs. 2A-2E are schematic, sectional illustrations of an area of a semiconductor wafer, 5 showing formation of hole 26 under different process conditions. In the exemplary application shown in these figures, hole 26 is meant to provide a contact to a region 34 of substrate layer 28 that contains TiSi₂ for enhanced conductivity. Region 34 is typically part of a 10 gate structure, formed within layer 28 by methods known in the art. Oxide layer 30 typically comprises materials such as undoped silicon glass (USG) or boron phosphorus silicon glass (BPSG) or low-k dielectrics, with the possible addition of a nitride barrier layer (for 15 example, Si₃N₄, not shown) between the silicon substrate and the glass. The structure illustrated in these figures, however, is shown solely by way of example, and holes 26 may similarly be made in and adjacent to other structures.

[0053] Fig. 2A shows an ideally-etched, open hole, i.e., a contact hole that cleanly exposes region 34, as desired. The remaining figures in this figure set show the results of different process anomalies. In Fig. 2B, hole 26 is underetched, typically due to a problem in 25 the etching process or in the uniformity of layer 30, for example. Consequently, the area of region 34 that is exposed at the base of hole 26 is smaller than desired. As a result, the specimen current generated when hole 26 is irradiated by an electron beam is smaller than the 30 benchmark current generated for the ideally-etched hole shown in Fig. 2A. When the underetched hole is filled with metal in order to contact region 34, the contact resistance may be higher than desired.

[0054] In Fig. 2C, the etching process is too strong or has continued for too much time, leading to overetching of hole 26. In this case, the specimen current will typically be greater than in the case of 5 Fig. 2A. Overetching may have a deleterious effect on region 34 and on other structures, and may also lead to the deposition of contaminants at the base of hole 26. In this case, the specimen current will be smaller.

[0055] Fig. 2D shows underetching, in which hole 10 26 stops short of reaching region 34, typically due to an incorrect etching process or an insufficient etching time. The measured specimen current for hole 26 in the present figure is low, and the subsequent contact resistance, following metal fill, may be substantially 15 higher than desired.

[0056] Finally, in Fig. 2E, hole 26 is properly etched. However, a contaminant 38, such as photoresist 20 polymer residue or dielectric residue, is deposited at the base of the hole. This contaminant typically causes a decrease in the measured specimen current as compared with the measured specimen current of an ideally etched hole, and the contaminant may cause a high contact resistance following metal fill.

[0057] In general, when a wafer is irradiated 25 with an electron beam, and this process reaches equilibrium, the relationship between the specimen current (I_{specimen}), the primary current (i.e. the current of the irradiating electron beam - I_{primary}), and the current of secondary electrons emitted from the wafer, 30 including scattered electrons ($I_{\text{secondary}}$), is expressed by the following equation, as is known in the art.

$$I_{\text{primary}} = I_{\text{secondary}} + I_{\text{specimen}} \quad (1)$$

When specimen current is measured, the surface of the wafer may be biased with a negative precharge, as described in the above-mentioned U.S. Patent Application 5 10/434,977. One effect of this precharge is to keep a large portion of the secondary electrons generated within the contact openings from leaving the wafer surface, thereby reducing $I_{\text{secondary}}$ and increasing I_{specimen} .

[0058] Referring to Fig. 2D, the sensitivity of 10 measured I_{specimen} to the thickness of residual dielectric material in layer 30 between the base of hole 26 and region 34 is related to the difference in the secondary electron (SE) yield and to the difference in conductivity between the materials of layer 30 and of region 34. 15 Typically, the secondary electron yield of dielectric materials is about twice the yield of semiconductor or conducting materials, for low electron beam energies, typically $< 1\text{kV}$. On the other hand, because of the low conductivity of the dielectric material in layer 30, the 20 measured I_{specimen} is roughly inversely proportional to the residual dielectric thickness for contact holes that are slightly underetched, and is close to zero for substantially underetched holes. Therefore, for a given contact hole or group of contact holes in a known 25 location on a wafer die, the measured I_{specimen} is a sensitive indicator of dielectric residual thickness in the approximate range of 0 to several tenths of nanometers. Furthermore, the measured I_{specimen} at the same location on different dies should be consistent over the 30 entire wafer, and differences in the measured values may be indicative of process non-uniformities. These non-uniformities and other process defects may be detected using the methods of specimen current mapping described hereinbelow.

[0059] Reference is now made to Figs. 3A-3D, which schematically illustrate another application of the methods of specimen current mapping provided by the present invention. Figs. 3A and 3C, which are sectional 5 illustrations of areas of a semiconductor wafer, showing well-formed holes 26, which are in proper alignment (Fig. 3A) or misalignment (Fig. 3B) with underlying contact holes 32. (This type of misalignment is also known as overlay misregistration.) Figs. 3B and 3D are schematic 10 top views of the respective areas shown in Figs. 3A and 3C. In the exemplary application shown in these figures, hole 26 is meant to line up with underlying hole 32, which is filled with a metal 31, such as tungsten. (Hole 32 is assumed to have been formed in an underlying layer 15 29 in a previous processing step.)

[0060] The alignment or misalignment of holes 26 and 32 may be detected by directing an electron beam toward hole 26 and measuring I_{specimen} values. When an acceptably etched and correctly aligned hole is formed, 20 as shown in Figs. 3A and 3B, fill metal 31 completely fills the view of the bottom of hole 26. Therefore, when an electron beam is directed to irradiate the area of hole 26, a relatively high value of I_{specimen} is measured. On the other hand, when hole 26 is incorrectly aligned 25 with hole 32, as shown in Figs. 3C and 3D, the view of the bottom of hole 26 is filled partly by fill metal 31 and partly by the material of layer 29 (which may be dielectric or semiconductor material). When I_{specimen} is measured in this misaligned configuration, its value is 30 typically less than that for the correctly aligned holes of Figs. 3A and 3B.

[0061] The variation in the value of I_{specimen} in the two examples above provides an indication of photolithographic misalignment, which may have occurred

at various magnitudes over the entire wafer, or in a certain area or areas of the wafer. By mapping I_{specimen} over the wafer surface, the magnitude, nature, and cause of the misalignment may be deduced. A lithography 5 station that was used in producing the contact holes in the wafer may be adjusted, based on the map, in order to prevent or minimize the misalignment in wafers produced subsequently. Note that the hole configuration of Figs. 3A-3D is shown here solely by way of example, and the 10 method exemplified by this figures may similarly be applied to evaluate the alignment of other types of contact openings, as well.

[0062] Reference is now made to Fig. 4A, which is a block diagram that schematically illustrates a 15 station 40 for contact hole inspection and specimen current mapping, in accordance with an embodiment of the present invention. Station 40 comprises a chamber 42, containing a motion stage 44 on which wafer 20 is placed during inspection. An electron gun 46 directs an 20 electron beam at wafer 20, while an ammeter 48 measures I_{specimen} generated in the wafer. The ammeter is electrically coupled to the semiconductor or conducting layer at the bottom of the contact holes of interest (such as layer 28, shown in Fig. 1B), optionally by means 25 of contact pad 33.

[0063] The electron beam generated by gun 46 is scanned so as to irradiate multiple, different locations over a region of the wafer or over the entire wafer. The beam diameter defines the field of view (FOV) of the 30 measurement, which may be adjusted so that at each location, the beam irradiates a single contact hole or a group of contact holes, such as two or more of the holes in pattern 22 (Fig. 1), or even all the holes in the pattern simultaneously. For this purpose, the FOV may

vary between about 0.1 μm and hundreds of μm . The electron energy of the gun is typically variable, between about 100 and 5000 eV, so as to cover both positive and negative charging domains of the materials in wafer 20.

5 (The positive charging domain is the range of electron energies in which the total yield of secondary and backscattered electrons from the surface layer is greater than 1, while the negative charging domain is the range in which the total yield is less than 1. These

10 phenomena, which are well known in the art, are described by Yacobi et al., in Chapter 2 of *Microanalysis of Solids* (Plenum Press, New York, 1994), which is incorporated herein by reference.) A suitable electron gun for this purpose, for example, is a thermal field emitter,

15 produced by Denka or FEI.

[0064] Stage 44 positions wafer 20 so that a given contact hole or group of contact holes at each location that is to be irradiated is properly located under the beam of gun 46. Stage 44 may comprise an x-y-theta or an R-theta (translation/rotation) stage. The contact holes thus measured may comprise special test patterns, such as pattern 22 (Figs. 1A and 1B), or they may, alternatively or additionally, comprise functional contact holes to be used in microelectronic devices

20 fabricated on the wafer. I_{specimen} is measured as the beam irradiates the proper locations, and a specimen current map (shown hereinbelow in Fig. 6) is created. The measurements are typically made at the same location on all the dies on the wafer. Alternatively, the

25 measurements may be made only on certain, selected dies, or at multiple locations on some or all of the dies. The contact hole locations evaluated in this manner may be chosen for assessing etch quality, overlay misregistration, or both, or for assessing other process

characteristics. The locations thus selected are typically representative of the process characteristics of the die on which they are located or of an area of the wafer containing multiple dies. If desired, a number of 5 different types of contact openings may be chosen and evaluated.

[0065] Optionally, a reference measurement of the specimen current is performed adjacent to each contact hole (or group of contact holes) for which I_{specimen} 10 is measured, or at least adjacent to certain contact holes. The reference measurement is performed at a small distance from the contact hole measurement location, typically in an area of the die without contact holes, in which the specimen current thus measured is expected to 15 be close to zero. The reference I_{specimen} value is subtracted from the contact hole I_{specimen} value, and the resultant difference specimen current value is used in the specimen current map.

[0066] Optionally, a secondary electron image is 20 measured simultaneously using a secondary electron detector 49, as is known in the art. The positioning and operation of gun 46 and stage 44 are controlled by a main controller 50, via a gun control unit 52 and a stage control unit 54. Typically, a pre-alignment unit based 25 on an optical microscope (OM) 56 is used by controller 50, via an OM control unit 58, to locate the pattern on the wafer for positioning and alignment purposes. Suitable microscopes for this purpose are made, for example, by Optem (Fairport, New York). During 30 operation, a vacuum is maintained in chamber 42 by a vacuum pump 60, which is also controlled and monitored by controller 50, via a vacuum control unit 62. A robot 64 inserts wafers into chamber 42 and removes them from the chamber. Controller 50 communicates with the robot via a

robot control unit 66. Robot 64 is preferably used to transfer wafers to and from other stations in a cluster tool (not shown).

[0067] After positioning stage 44 and firing gun 46 to irradiate the selected contact holes and, optionally, reference areas, controller 50 receives the I_{specimen} values measured by ammeter 48. The controller uses these values in preparing a specimen current map, which is typically displayed on a user workstation 68. 10 An exemplary map is shown in Fig. 6. Test results are evaluated and whatever corrective action may be necessary is implemented. The evaluation typically compares the measured specimen current values to benchmark values that have been established for the expected hole size, 15 materials, etch conditions and other applicable process parameters, as well as comparing the specimen current values that have been measured on different dies across the wafer. Wafer-to-wafer comparisons of specimen current maps may also be made. The corrective action may 20 include performing further etching, if the contact holes are underetched (as shown in Figs. 2B or 2D), or removing polymer residue that may have been deposited at the bottoms of the holes (as shown in Fig. 2E). Additionally or alternatively, the corrective action may include 25 process and alignment adjustments to the photolithography station and/or etching equipment that was used in producing the wafer currently measured.

[0068] Fig. 4B is a schematic, sectional illustration showing angled irradiation of contact hole 26 by an electron beam 130, in accordance with an embodiment of the present invention. Tilting of electron beam 130 may be achieved by either mechanical means or by the use of electron optics to control the beam, or by a combination of both techniques. Some CD SEM systems,

such as the Applied Materials NanoSEM3D, provide this sort of beam tilt capability. Because the electron beam is tilted, the primary beam electrons typically pass at an angle through any residual dielectric layer or a 5 contaminant 138 that may remain at the bottom of the contact hole. As a result, the path of the electrons through the residual layer or contaminant is longer, and the electrons are more likely to interact with the residual layer or contaminant. Therefore, the 10 sensitivity of the specimen current measurement to thin residual dielectric layers and contaminants in the contact holes is enhanced.

[0069] Furthermore, the tilt angle of beam 130 may be chosen so that a majority of primary beam 15 electrons do not strike the bottom of the contact hole. This condition can be achieved when the following geometrical condition is satisfied:

$$\alpha > \arctan(1/AR),$$

20

wherein α is the tilt angle, and AR is the aspect ratio (ratio of depth to diameter) of the contact hole. As a result of this tilt angle, the primary electrons hit the side wall of the hole 26 rather than the bottom. The 25 electron bombardment causes emission of secondary electrons with low energy (typically <50 eV). The low-energy secondary electrons can be forced down to the hole bottom, rather than moving out of the hole, by negatively precharging a surface 132 of the wafer around the hole. 30 (Such precharging may be accomplished, for example, by operating the electron beam at an energy in the negative charging domain of surface 132 before making the specimen current measurement.) If the contact hole is etched

properly (with no residue left at the bottom), the low-energy electron flow will pass through substrate 28 and will thus be measured as a specimen current by ammeter 48. If a thin residue (even tens of Angstroms thick), 5 such as under-etched dielectric or contaminant 138, is left after the etch, the specimen current will be much lower, due to low penetration depth of the low-energy secondary electrons.

[0070] By contrast, when electron beam 130 10 operates at higher energy and is not angled, the energetic primary electrons reach the bottom of hole 26. In this case, the primary electrons pass easily through contaminant 138. Therefore, holes with particularly thin residues cannot be readily distinguished from holes that 15 have been etched satisfactorily. Angling electron beam 130 substantially enhances sensitivity of the specimen current measurement to very thin residues at the hole bottom. This method is particularly useful in detecting fluorocarbon polymer residue, organic photoresist 20 residue, and extremely thin oxide, nitride or other dielectric residue (including low-k dielectric with a corresponding stop layer). It can be performed by station 40 in-line, providing closed-loop monitoring of reactive ion (plasma) etching, photoresist ashing, and wet polymer 25 cleaning steps.

[0071] Fig. 5 is a flow chart that schematically illustrates a method for specimen current mapping, in accordance with an embodiment of the present invention. As described above, wafer 20 is first etched to produce 30 holes 26, at an etching step 505, and the wafer is then transferred to chamber 42 of station 40, at a transfer step 510. Stage 44 is operated to correct for any positioning offset and to align the scribe lines on wafer 20 substantially parallel to the translational movement

of stage 44, in a global alignment step 515. Stage 44 is then operated to allow focusing measurements to be made by OM 56 across the surface of wafer 20, thereby creating a map of height variations across the wafer surface, at a 5 create focus map step 520. (The focus map is used by the main controller 50 and the gun control unit 52 to control and predict focus current for electron gun 46 at each measurement location on the wafer.) Alternatively, other methods known in the art may be used to control the beam 10 focus, without the use of a focus map. The difference in optical and electron beam focal planes, also known as focal offset, is determined in a learn focus offset step 525. This is done by comparing the focal length that is measured by the OM to the focal length measured by the 15 SEM. The focus offset is the difference between the two measurements.

[0072] Based on preselected measurement locations of one or more contact openings in locations across wafer 20, the wafer is positioned at a location, 20 gun 46 is fired, and a specimen current measurement is made, at a sample measurement step 530. The current is recorded while scanning the electron beam over a field of view that is typically a few microns across (for example, 3 microns). Alternatively, the field of view may be 25 larger or smaller, depending on the number of contact holes to be irradiated at each location, as described above. The bandwidth of ammeter 48 may be much lower than the bandwidth of the scan, so that it records an average, quasi-DC current flowing from the scanned field 30 of view to the ground.

[0073] A reference measurement may be performed adjacent to the contact opening or openings at the present location, as described hereinabove, in a reference measurement step 535. The reference current

value ($I_{reference}$) measured in step 535 is subtracted from the specimen current value ($I_{specimen}$) measured in step 535, and the resultant current value and location coordinates are recorded, in a result recording step 540.

5 Alternatively, $I_{reference}$ is not measured and step 540 is not performed. In this case, $I_{specimen}$ and location coordinates are recorded in step 540.

[0074] A check is performed to determine whether there are additional locations at which one or more 10 contact openings are to be measured, at program checking step 545. If so, the controller selects the next location, repositions the wafer and measures accordingly, at step 530. Steps 530-545 are repeated until there are no further locations to measure. The data recorded at 15 step 535 are used to create a specimen current map (shown hereinbelow in Fig. 6), at a mapping step 550.

[0075] Fig. 6 is a schematic representation of a specimen current map 600, showing the specimen current measured at multiple locations across wafer 20, in 20 accordance with an embodiment of the present invention. A key 610 shows a range of specimen currents versus shading gradations. (Typically, key 610 shows color shading.) Axes 620 represent dies or other convenient coordinate location indicators. Corresponding specimen 25 currents are indicated with appropriate shading at respective locations on the map. In map 600, one specimen current value is shown for each wafer die. Alternatively, more or fewer specimen current values may be shown on map 600. Although map 600 is shown as a 30 graphic representation, it may be alternately or additionally maintained as a numerical representation, such as in vectorial form.

[0076] As shown in map 600, the magnitude of the specimen current across most of the dies on the wafer was

high (i.e., strongly negative). On the upper and lower edges of the wafer, however, much lower specimen current magnitude was measured. It is noted that this is not necessarily so and higher specimen current magnitudes can 5 be measured on the upper and lower edges of the wafer. These low values may be indicative, for example, of non-uniformity in the etch process or of contact misalignment. The form of map 600 typically gives an indication of the type of process defect involved, so 10 that appropriate corrective steps can be taken.

[0077] Although the embodiments described hereinabove are directed particularly to contact hole monitoring, the principles of the present invention may also be applied to other quality control tasks. A wafer 15 specimen current map may be useful in monitoring not only etching and lithography steps, but also deposition (including material film thicknesses), and photoresist application and uniformity. The methods of the present invention provide an indication both of the width of such 20 features and of the thickness of layers making up the features. These methods can be adapted for use not only before metal deposition, as in the embodiments described above, but also after metal deposition to inspect contacts, interconnects and metal lines for potential 25 disconnects, short circuits, and other defects. Test station 40 may be integrated into a cluster tool for in-line monitoring of parameters described hereinabove.

[0078] It will thus be appreciated that the 30 embodiments described above are cited by way of example, and that the present invention is not limited to what has been particularly shown and described hereinabove. Rather, the scope of the present invention includes both combinations and subcombinations of the various features described hereinabove, as well as variations and

modifications thereof which would occur to persons skilled in the art upon reading the foregoing description and which are not disclosed in the prior art.